

# The development and evaluation of 3-dimensional models of cold flow in internal combustion engines

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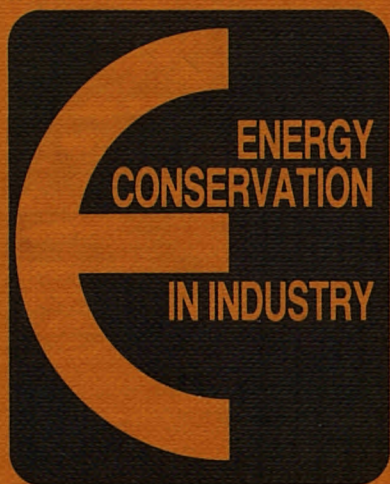
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# THE DEVELOPMENT AND EVALUATION OF 3-DIMENSIONAL MODELS OF COLD FLOW IN INTERNAL COMBUSTION ENGINES

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## Summary

The aim of the research described here is to produce a computer program, which is capable of computing unsteady 3-dimensional turbulent air motion and heat transfer in the combustion chambers of reciprocating engines under motoring conditions. The computer program will be able to treat a limited but useful range of geometries. The reliability and accuracy of the code is being evaluated by comparison with experimental data generated as part of this research and extracted from other sources in the literature.

The computer program uses novel numerical techniques to provide both an accurate, high resolution, representation of complex geometries and economy in the use of computer time and storage space. The experimental data are of high quality and comprise measured values of mean and rms velocities around the inlet valves, in addition to the flow in the main cylinder region.

## 1. INTRODUCTION

The present development of a 3-dimensional model of the in-cylinder flow processes is based on earlier work at Imperial College(1-4) on 2-dimensional axisymmetric models of these processes. Although the accuracy of these multi-dimensional models is currently only moderate, they are nonetheless already capable of providing information to engine designers which is both useful and would be difficult and expensive to obtain by any other means.

In general the flow fields in practical engines are almost always 3-dimensional in form. For example, the flow generated during induction is invariably 3-dimension, due to the almost universal practice of siting the inlet valve towards the edge of the bowl; and further 3-dimensionality may be produced if the combustion chamber is asymmetrical.

Most axisymmetric methods are in principle amenable to straightforward extension to three dimensions and there are instances where this has already been done, eg (5,6). It is however very difficult to achieve acceptable computer storage and time requirements, especially when the computational grid is made sufficiently dense to reduce numerical truncation errors to tolerable levels. Consequently, in the present work we have relied on novel techniques for gridding which provide an accurate, high resolution representation of complex geometries by using arbitrary curvilinear-orthogonal grids. In addition we report the use of a new solution algorithm which provides a

marked improvement in the economy with which computations can be carried out for turbulent flows with time varying mean properties.

## 2. DESCRIPTION OF THE MODEL

Multi-dimensional models can be characterised in terms of the way in which the computational grid is fitted to the flow domain, the discretisation of the differential conservation equation governing the flow processes on this grid, the method of solution of the resulting algebraic equations, and the mathematical representation employed for the turbulence. The present approach is described below in these terms.

### (a) Coordinate system and grid

The grid is illustrated in Figure I and has the following features:

- (i) Between the piston crown and cylinder head it is arbitrary curvilinear-orthogonal in diametral planes (Figure I(a)) and rectilinear in other views (Figure I(b)). In addition, it expands and contracts with the motion of the piston and valves, so as to maintain good resolution at all stages in the engine code.
- (ii) Within recesses, where they exist, in either the piston (Figure I(b)) or the cylinder head it is curvilinear-orthogonal in either plane or elevation (Figure I(b)) views.

With this arrangement it is possible to treat chambers having off-centre inlet valves or piston recesses, within certain constraints.

### (b) Discretisation

Discretisation is performed by the finite-volume method, as in our earlier work(1-3). Each of the conservation equations for mass, momentum and energy, and representations of the turbulence approximations, is integrated over imaginary control volumes surrounding each mesh intersection or "node" in Figure I. The integrations are performed using an approximation which includes upwind differencing in the representation of the convection transport terms, and forward differencing in the temporal discretisation. This process produces one equation for each dependent variable and grid node. The equations are usually coupled due to inherent linkages in the original differential equations, whose non-linearities are also carried through.

### (c) Solution algorithm

There are two key facets to the solution of the discretised equations namely, the manner in which the (often non-linear) inter-linkages between variables are handled (especially those between velocity and pressure) and the method of solution of the resulting quasi-linear simultaneous equations. In the present work a novel algorithm known as "PISO" is used to deal with the inter-linkages between variables. This approach operates by linearising the equations about the "old" time level and using a combination of operator-splitting and predictor-corrector techniques to solve the linearised equations. The sequence of operations performed at each time step is as follows:

- (i) the momentum equations are solved using the prevailing pressure field to estimate the pressure gradients they contain (the predictor step).

- (ii) first-stage corrections are then calculated for the pressures. These corrections are chosen so that when substituted into abbreviated and approximate forms of the momentum equations they yield velocity corrections which satisfy the mass conservation requirement when applied to the velocity field emanating from (i). The pressure correction field is itself obtained through solving simultaneous equations based on the latter requirement.
- (iii) second-stage corrections are then made to both velocities and pressures which maintain mass conservation while compensating for the momentum balance errors introduced in (ii). This again involves a solution of simultaneous equations for the pressure corrections.

The calculation of temperature and other variables is embedded in the above sequence at the appropriate stages and performed using similar techniques.

At each stage it is necessary to solve a set of simultaneous linear equations in one variable. This is currently done using an efficient block-iteration technique. Methods of potentially even greater efficiency are also being investigated.

#### (d) Other features

The wall boundary conditions are treated using a simplified boundary-layer model of the near-wall flows to calculate the wall shear stresses and heat fluxes.

Inlet flows are determined by calculating the instantaneous mass flow via orifice-type relations and imposing either measured (when available) or assumed distributions to the velocities and other variables in the plane of the valve orifice. The alternative of attempting simultaneously to calculate the in-cylinder and inlet port/valve assembly flows is in our view not currently feasible due to the excessive requirements on computer storage and time.

In addition the computer code is written so that it can exploit the advantages of vector processing machines like the CRAY-1 and CDC Cyber 204, while not impeding its use of conventional serial machines.

#### (e) Treatment of turbulence

Here we continue the well established practice of employing ensemble averaging to eliminate the need of directly calculating the small-scale turbulent motions. The particular turbulence model chosen is the k- $\epsilon$  model which represents the effects of turbulence as an effective viscosity which is in turn computed from the turbulence kinetic energy and its dissipation rate.

As a result of these choices the computation yields only ensemble averaged information, rather than cycle resolved velocities. In addition, since the turbulence models inevitably contain a degree of empiricism and associated uncertainty, this introduces additional sources of error into the results.

In principle, alternative approaches exist which could be used to partially overcome restrictions but they are currently too expensive for practical applications.

### 3. EXPERIMENTAL APPROACH

The complexity of the three-dimensional turbulent unsteady and compressible flow in internal combustion engines suggests that the experimental programme should involve the investigation of one parameter at a time and initially make use of simplified flow arrangements. A versatile test rig was built for this purpose and allows both pressure drop and velocity measurements to be made for a variety of intake valve geometries in axisymmetric and 3-dimensional engine configurations. Special provision was made for the measurement of two velocity components in the exit plane of the intake valve to fulfil the requirement of detailed initial conditions for the computer code. The test rig allows the quantification of the influence of valve/port geometry, cylinder wall confinement and valve eccentricity with respect to the cylinder axis, on the flow field in the exit plane of the valve and immediately downstream. Comparison of results obtained under steady and unsteady flow conditions also allows the assessment of the validity of the quasi-steady flow assumption usually made for the induction process.

### 4. EXPERIMENTAL TECHNIQUES

#### 4.1 Pressure Drop Measurements

The performance of a port/valve configuration can be characterised by the discharge coefficient which gives a measure of the obstruction caused by the valve during the induction stroke. For this purpose, the air mass flow rate was measured by an orifice meter with a Betz micromanometer to determine the pressure drop across the valve. Comparison of the measured mass flow rate with that expected for an ideal nozzle under the same pressure drop provides a measure of the quality of the intake valve and possible discontinuities of the discharge coefficient curves with valve lift indicate flow separation from the sealing edges of the valve. This method was used to assist the construction of an intake valve which provided well defined intake flows in the engine cylinder; this valve arrangement would also give rise to good performance under operating engine conditions. The discharge coefficient of the intake valve is used as an input to the computer code as it defines the air mass indrawn in the cylinder at every instant of the intake stroke.

#### 4.2 Velocity Field Measurements

The nature of the in-cylinder flows in internal combustion engines requires a method of measuring velocities which is independent of temperature and density variations and, if possible, non-intrusive. In the light of previous experience, eg (7,8) the laser-doppler anemometry technique was used here (Figure II). A 5 mW helium-neon laser was used in conjunction with a diffraction rotating grating which split the laser beam into two and simultaneously shifted the frequency of the resulting beams. A system of lenses focussed the two beams to form an interference pattern in a measuring volume. Micron-sized particles were added and on crossing the measuring volume, scattered light with frequency directly proportional to the magnitude of the velocity component normal to the sensitivity vector of the measuring volume. The scattered light was collected by a photomultiplier, its frequency measured by a digital counter and then processed in a microcomputer interfaced to the measuring system. Mean and fluctuating values of the three velocity components were measured with an accuracy of 2 and 4% respectively using the ensemble averaging method of individual realisations.



The optical access required by the laser-doppler technique was provided by using transparent engine cylinders made of cast acrylic (perspex).

## 5. RESULTS

### 5.1 Valve Geometry

The need for an improved design of the intake valve was shown in earlier research(9) where measurements with a 60° seat angle valve revealed exit-plane profiles with separation which increased with lift and, with high lifts, stemmed from the valve face and seat. The result of this flow detachment was a poor discharge coefficient and a considerable variation of intake flow angle with valve lift. In the present work a 45° seat angle valve was tested and gave an increased discharge coefficient by up to 15%, compared with the 60° valve. Pressure drop and velocity measurements, however, showed that the flow still detached from the sealing edges of the valve but to a lesser extent than before. A considerable improvement in valve behaviour was achieved by simply rounding the edges of the valve and valve seat. The discharge coefficient was improved and the flow detached only from the valve seat at medium to high lifts. Radial and axial velocity component measurements made at the exit plane of the valve showed that the flow angle changes only slightly with valve lift due to the single separation of the flow from the valve seat, Figure III. In addition a considerable Reynolds number dependence was found to exist of both the discharge coefficient and the valve lifts where separation occurs, but only at low Reynolds numbers. Finally, it was shown that a good representation of the discharge coefficients throughout the cycle is obtained by assuming constant flow rate corresponding to the mean piston speed, except for very small lifts.

### 5.2 Valve Confinement

The 45° seat angle valve with rounded corners was used to quantify the influence of valve confinement and cylinder wall proximity on the velocity field in the exit plane of the valve. Axial and radial velocity components have been measured at the exit plane of an unconfined valve mounted on a flat plate simulating the cylinder head and compared with similar measurements obtained in both axisymmetric and off-centre valve geometries confined by a cylinder. The results show that cylinder wall confinement caused the flow to separate from the valve seat at lower lifts than in the unconfined valve case. Furthermore, with the off-centre valve configuration a non-uniform distribution of the exit velocities around the valve was observed as a result of the upstream effect of the non-uniform development of recirculation at the cylinder head corner. The discharge coefficient was found to remain equal to that obtained in the axisymmetric configuration and showed that the valve eccentricity caused a slight redistribution of exit-plane velocities and flow angled around the valve, but no changes in the total air mass flow rate. These results show that quantifying valve performance with its discharge coefficient, as in usual practice, is not adequate for the refined information needed for internal combustion engine modelling.

## 6. CONCLUSIONS

Preliminary comparisons have been made between the results of the computer program and existing experimental data. During the course of the next few months detailed comparisons will be made between the experimental data described above and predictions of the code, using the measured inlet boundary conditions.

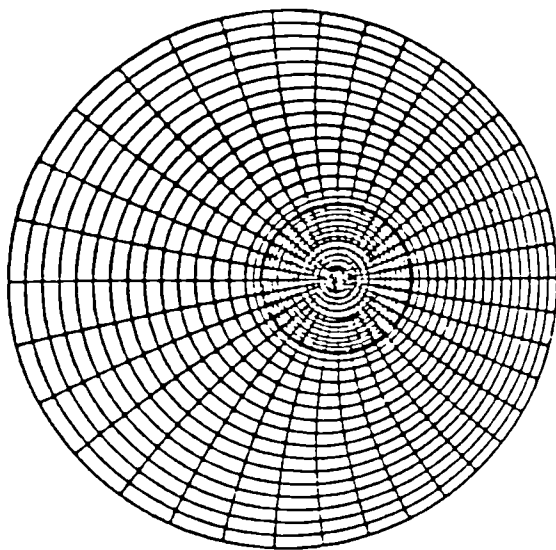


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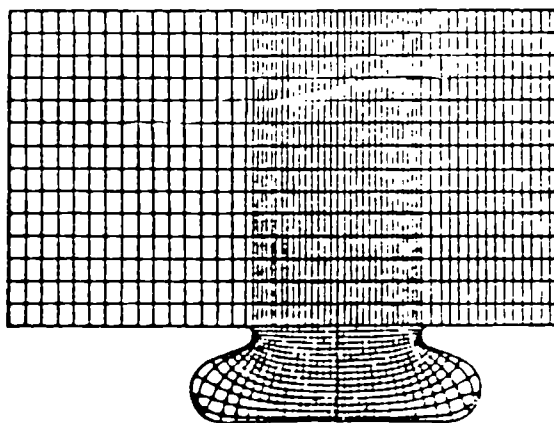
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(a) Diametral planes



(b) Axial planes

Figure I: Illustration of Grid

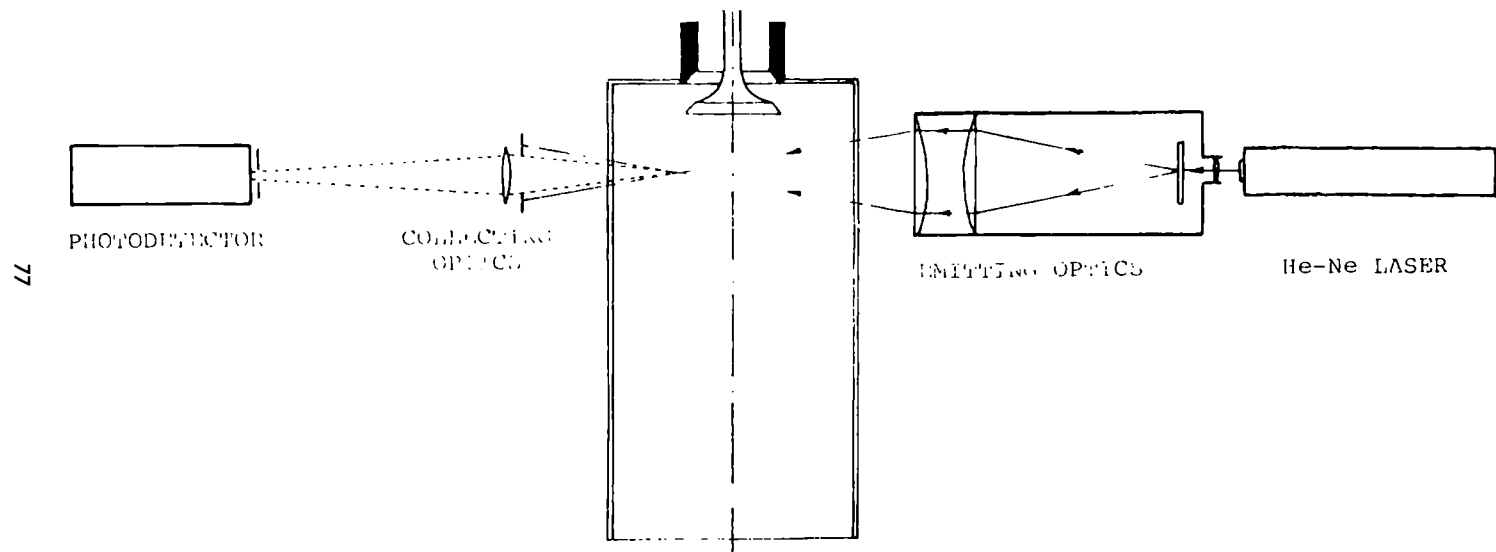
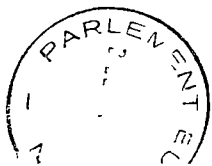


Figure II: Laser Anemometer Layout for Flow Measurement



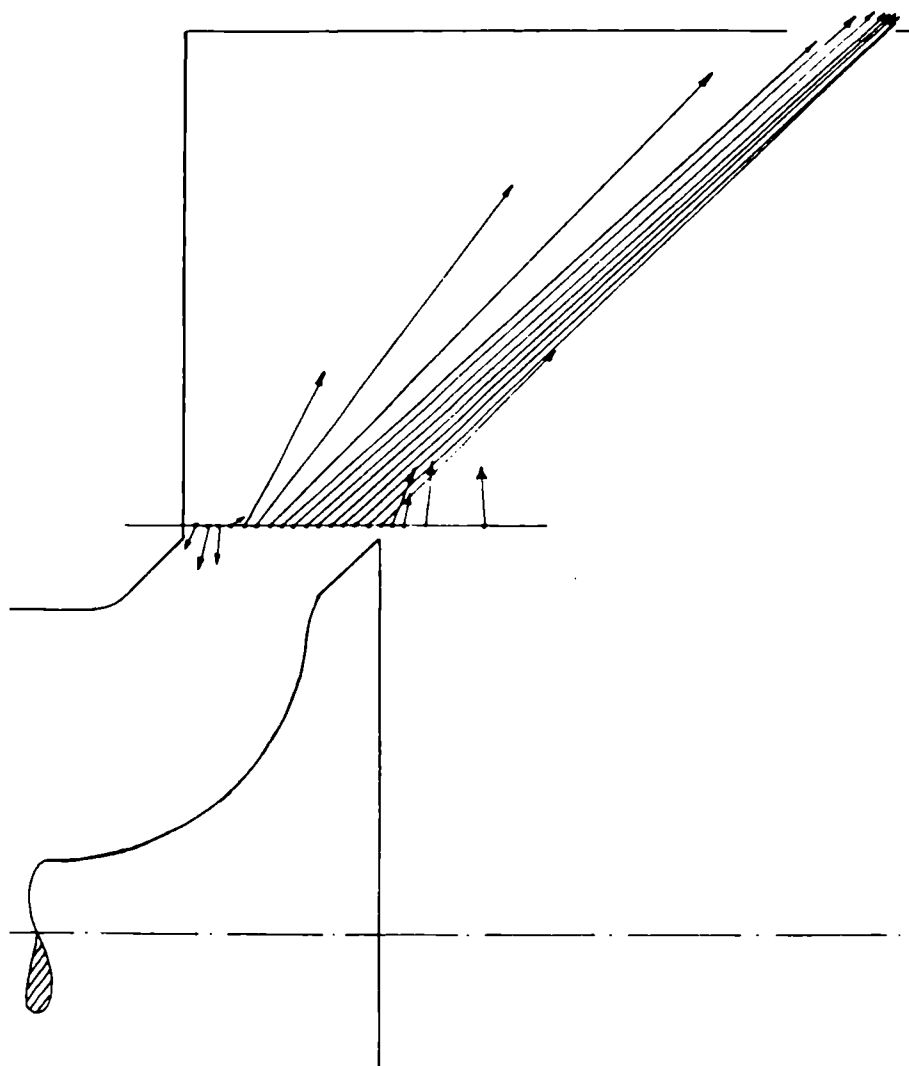


Figure III: Flows through the Valve Orifice

## **ENERGY CONSERVATION IN INDUSTRY**

Results of the European Communities  
Energy R & D Programme (1979-1983)

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*Edited by*

A. S. STRUB and H. EHRINGER

*Commission of the European Communities  
Directorate-General for Science, Research and Development, Brussels, Belgium*

The International Seminar "Energy Conservation in Industry" organized by the Commission of the European Communities in cooperation with the Verein Deutscher Ingenieure (VDI) highlighted the results of energy conservation projects carried out within the framework of the Communities Second Energy R & D Programme (1979-1983). The seminar was also intended to convey these results to representatives of national authorities, public, industrial and financial organizations. In an opening session, recognised energy experts illustrated the need for energy conservation research and commented on the potentials of various technologies in this field. This was followed by the results of research work carried out by contractors. This information was presented in four plenary sessions and four poster sessions on energy saving technologies, engines and flywheels, electrical energy storage devices and industrial applications of energy saving technologies. During each session an overview of the work was given by a rapporteur and some contractors. At the end of the conference, overall conclusions and recommendations were developed by the Conference Chairman Dr. A. Strub, Director at the Commission of the European Communities and by the Session Chairmen.